ENGINEERING CASE LIBRARY

ECL 98 A

Integrated Distributed Amplifier

at

General Electric Company (A)

In May 1960, when Ed Craig was asked to work on the design and development of an "integrated distributed amplifier", work on the project had already been in progress for several years. The project, which was started on August 12, 1957, was headed by Charles Mayer, an electrical engineer in the Microwave Business Section of the General Electric Company in Schenectady, New York, and was intermittently active up to the time that Ed was asked to join the development team.

The research and development effort on the "integrated distributed amplifier" was supported by the Army Signal Corps who wanted an amplifier operable in the 50 to 500 MHz frequency range with a power gain of 20 db and one which could deliver 25 watts of power to a load. Problems in the mechanical and electrical design were encountered. One such problem was encountered in the accurate mathematical model of the grid-plate structure of the tube in which calculated design parameters did not agree with experimentally measured values. Ed was assigned to this project with the view of taking a fresh look at the mathematical model of the tube.

This case was prepared by Professor Homi D. Gorakhpurwalla of South Dakota State University while attending the Case Methods Institute at Rensselaer Polytechnic Institute, Troy, New York, supported by the National Science Foundation.

Microwave Business Section

Complete engineering, laboratory, and manufacturing facilities are maintained by the Tube Department's Microwave Tube Business Section at Schenectady, New York, for the development, design, and production of all types of power tubes, associated components, and circuitry for commercial, industrial, and military applications. The Microwave Tube Business Section totals approximately 500 personnel, consisting of approximately 45 engineers, scientists, and consultants augmented by experienced technicians, craftsmen, and other supporting personnel.

Since electron tubes utilize essentially all of the known natural elements and involve almost every branch of the physical sciences, the engineering staff numbers among its members not only electrical, electronic, and mechanical engineers, but also personnel trained in physical chemistry, physics, ceramics, and metallurgy.

To aid them in their assigned tasks, members of the engineering staff have at their disposal modern laboratory facilities for developing and testing nearly any type of electronic device under closely controlled, precise conditions. This facility is equipped to design, develop, and produce any electron tube ranging in size from miniature tubes up to large multimegawatt tubes. Personnel in the engineering laboratory assemble tubes according to engineering specifications, and since it is extremely important for tube parts to be kept contamination-free, the assembly operations are performed in a snow-white area under closely controlled conditions of temperature and humidity.

A testing laboratory, which can handle tubes ranging from button-size magnetrons to man-size klystrons; and a ceramic laboratory, where personnel fabricate ceramic parts of unusual complexity, form part of the Microwave Business Section facilities.

The section has an extensive analog computer facility for the expeditious and optimal handling of a variety of engineering analytic problems. Several digital computers are also available to the engineering staff of this section for use in their research programs.

Bill Teare, who has served with the General Electric Company since 1931 in various capacities, is the manager of engineering in the Microwave Business Section. In his opinion, "you can't sit back and relax on one profit making line". To illustrate his point he said, "even receiving tubes will someday be phased out of the market by solid state devices, although this phase out has been delayed by the advent of color T.V. Research and development effort, in the long run, produces usable devices and extends the state of the art. When the need for such devices arises, we can put the cost and marketing efforts into it for manufacture of them."

Besides the research and development efforts (R & D) that the company itself supports, the company bids on solicited and unsolicited proposals for R & D from private, industrial and governmental agencies. "It's generally not productive to respond to a solicited proposal if it is for extension of work which someone else has already done, but if you have worked on the idea first and can demonstrate that it is sound, it is possible to get support for it." In the last four years the section has concentrated more on solicited proposals than on unsolicited ones.

Bill guessed that about 50% of the R & D products end up in manufacturing. "The research ideas may be very good, the engineering development effort may also be good, but the product may not reach production because we may have guessed wrong on the possible market." He added that if an R & D project would cost $100,000 (to pick a number) a lot of "soul searching" would be required before the project was approved; one which would cost $25,000 would require a lot of "thought", while a project worth $2,000 would be given a "go ahead, if the idea looked good". Bill's opinion on government R & D is that "it normally does not pay off".

Background of Craig and Mayer

A professor from Union College, Schenectady, New York, Dr. Ed Craig has been working in the Microwave Tube Section of General Electric Company in Schenectady for several summers. He explains this arrangement as very satisfactory to him. "I am interested in research, but not the kind done in several of our universities today," he said. "I like to work on something that results in the development of a product, and you can do this if you work closely with people who can build a prototype model and test it in the laboratory."

Craig received his B. S. degree in Electrical Engineering from Union College in 1948 and his Sc. D. in Electrical Engineering from the Massachusetts Institute of Technology in 1954. During his last two years at M.I.T. he was an instructor in Electrical Engineering and a research assistant in the Digital Computer Laboratory there while preparing his thesis. His research involved the use of the computer in the solution of linear and nonlinear simultaneous equations. In September 1953, he joined the faculty of Northeastern University doing research in Communication Theory and teaching part time. Promoted to Associate Professor in 1955, he accepted a position at Union College as Associate Professor of Electrical Engineering in 1956.

In July 1956, he joined the Schenectady location of the General Electric Company, Tube Department, as a Consultant, a position which he still occupies. Since 1960 he has also been Professor of Electrical Engineering at Union College.

His experience includes research and development in the use of digital computers, communication theory, noise, field theory, circuit theory, voltage-tunable magnetrons, distributed amplifiers and klystrons.

In May 1960, Ed was asked to join Charles B. Mayer, and electrical engineer who was in charge of development work on an Army Signal Corps contracted project of building a tube for use in a distributed amplifier. The project was started on August 12, 1957 and was intermittently active up to this time.

Charles B. Mayer joined the General Electric Company upon graduation from City College of New York in 1951. His first four years were given to special assignments throughout the electronics-oriented sections of the company while engaged in the Advanced Engineering Program. During this period he worked on problems connected with radar systems planning, microwave circuits studies, transistor research, oscillator stability, antenna development, and traveling-wave tube research.

From 1955 through 1966, he was engaged in electron device research and development, first in the General Electric Research Laboratory and later in the Tube Department. During this period he worked on long pulse emission studies, high temperature circuits, extended interaction-tetrodes, integrated distributed amplifiers, and log-periodic electron devices. In January 1967 he transferred to the Missile and Space Department of General Electric where he is engaged in mission planning studies for interplanetary vehicles.

Ed said, "Mayer was asked to build a tube which would deliver 25 watts of power to a load with 20 db power gain and operable in the 50 to 500 MHz frequency range."

"From the very beginning, I think, the idea was to build tubes which could be used in a distributed amplifier rather than a cascade amplifier system," Ed explained. "Cascading individual tube amplifier stages, where the output signal from one stage becomes the input signal of the next stage tube, increases the gain of the overall amplifier. The total voltage gain of the system is then simply the product of the voltage gains of the individual amplifier stages."

From the equivalent mathematical model (see Exhibit A-1 and A-2) of one stage of the amplifier at high frequencies it can be shown that the gain (voltage) and bandwidth are not independent but related by the ratio

$$\text{(Voltage) Gain} \times \text{Bandwidth} = \frac{g_m}{2\pi(C_{pk} + C_{gk})}$$

where,

g_m = grid-plate transconductance

C_{pk} = plate-cathode capacitance

C_{gk} = grid-cathode capacitance

"For a given tube then," Ed explained, "the gain bandwidth product has an upper limit. The bandwidth of the amplifier can be increased somewhat by the introduction of an appropriate inductor in the plate circuit (see Exhibit A-3). This increase, however, is not significant enough to be useful in the design of an amplifier up to 500 MHz."

It becomes obvious then, that the tubes had to be designed and built more stringently or based upon a different concept which would separate the gain and the bandwidth of the overall amplifier system. A distributed amplifier concept would do just this.

Distributed Amplifiers

The principle of distributed amplifiers may be understood using a lossless transmission line terminated at both ends by its "characteristic impedance" Z_o. This line is fed by N current sources of equal amplitudes but with a time delay τ_k (or phase difference) between the first current source $I_1(t)$ and the K^{th} current source $I_k(t - \tau_k)$, where τ_k is equal to the time taken by a wave traveling from point A to point K on the line (see Exhibit A-4). Since a source I_o at any point on the line will induce two "waves" in opposite directions on the line of one-half the magnitude of the source current, and the phase relationship is such that all of these current waves traveling to the right add in phase while those traveling to the left add in an incoherent way, the magnitude of the total current reaching the load end to the right is $NI_o/2$, where I_o is the magnitude of each of the N current sources. The gain then is increased by increasing the number of current sources while the bandwidth is determined by the distributed inductance and capacitance of the transmission line.

The current sources may be tetrode tubes. Instead of connecting the tubes on the line and feeding them separately with a phase lead (or lag) between the successive tubes, they are fed by a separate transmission line called the "grid line". Then (see Exhibit A-5) the currents amplified by the tubes will add on the "plate line" in the manner required.

Mayer finally decided to use lumped parameter lines consisting of "Constant-K" filter sections. Analysis showed that such lines would yield an output current similar to that obtained using transmission lines but the bandwidth of the filter sections would now determine the bandwith of the amplifier (see Exhibit A-6).

In his design of the plate line, Mayer noted that he needed a high characteristic impedance which he chose to be 200 ohms. The transit time, grid spacings, and technology at that time, fixed the values of the grid to cathode, grid to screen and grid to ground capacitances. Also he found that in the grid line he needed a certain inductance to obtain its phase characteristics to be identical to the phase characteristics of the plate line. From these considerations he determined a value of 30 ohms for the characteristic impedance of the grid line.

$$Z_{o(\text{grid line})} = \sqrt{\frac{L_g}{C_g}} = 30 \text{ ohms.}$$

A model was suggested and built by a shop technician. Exhibit A-7 shows two such integrated distributed amplifiers built "back-to-back" for possible push-pull use. In the finished model the "exhaust tubulation" is "pinched off" and sealed. Exhibit A-8 shows a cross-sectional view of this devise.

The control grids were thin wires stretched between two ceramic plates with one wire missing between grids of two successive tubes (see Exhibit A-9). The "grid line" inductances (L_g) were small loops of single turn of wire connected between the grid sections. The "plate line" (see Exhibit A-10) inductances (L_p) consisted of a helical tape wire with taps at each turn and plate line capacitances were the capacitances between plates and ground. There were thirteen sections in each tube with 1/3 section on each end as terminating sections.

From the parallel plate capacitance assumption and the dimensions of the coil Mayer calculated these values as

$$C_{pk} = 1.2 \times 10^{-12} \text{ farads}$$

$$L_p = 29.34 \times 10^{-9} \text{ henrys}$$

Using the plate line equivalent circuit he calculated the characteristic impedance of this line to be

$$Z_{op} = \sqrt{\frac{L_p}{C_{pk}}} \frac{1}{\sqrt{1 - (\omega/\omega_{co})^2}} = 151 \text{ ohms}$$

where,

ω = operating frequency in radians/sec

ω_{co} = cut off frequency in radians/sec

and the cut off frequency as

$$f_{co} = \frac{(1/\pi)}{\sqrt{L_p C_{pk}}} = 1760 \text{ MHz.}$$

In the laboratory Mayer measured the following values:

Z_{op} = 190 ohms

f_{co} = 1390 MHz.

"We were aiming at a 200 ohms plate line characteristic impedance and got 190 ohms in the laboratory," Craig said. "Obviously, something had gone wrong in the calculations which showed this impedance to be 151 ohms. One thing that showed our amplifier to be sound in practice was the phase characteristics of the plate and grid lines. In order to have a distributed amplifier action," he continued, "it is very important that the phase characteristics of the plate and grid lines be linear and identical (see Exhibit A-11). Experiments on the model showed that they were identical and linear from 0 to 600 MHz so we knew that the idea was sound."

The differences between the experimental and calculated values were set aside due to the pressing need to concentrate on other problems. "We were pragmatic," he said. "We had mechanical problems with the grids; there were grid line losses which caused injected currents to decrease as they propagated along the grid line and hence presented problems of loss in gain and power."

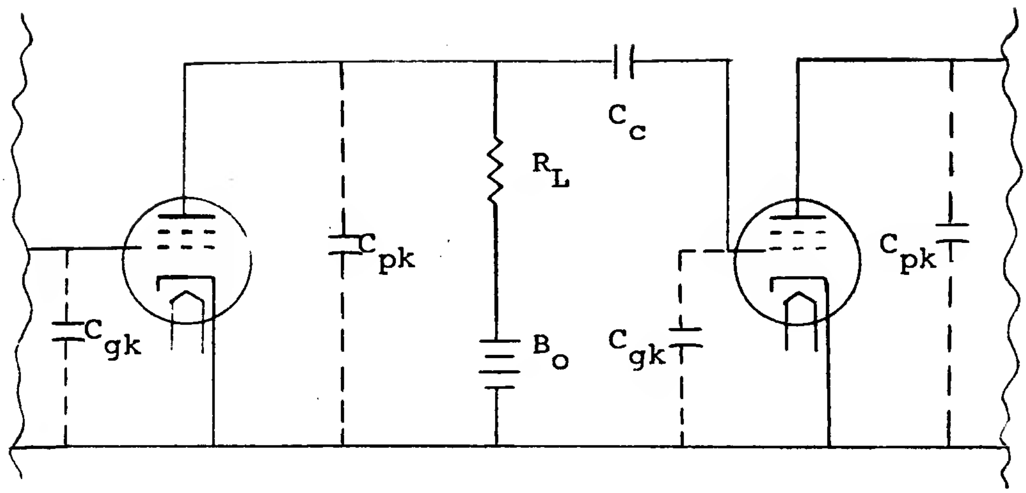


Exhibit A - 1 R-C Coupled Tetrode Amplifier

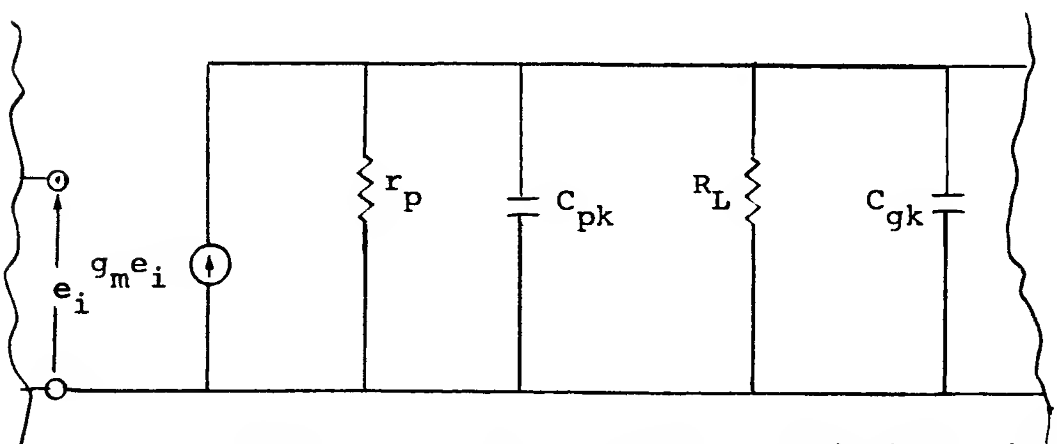
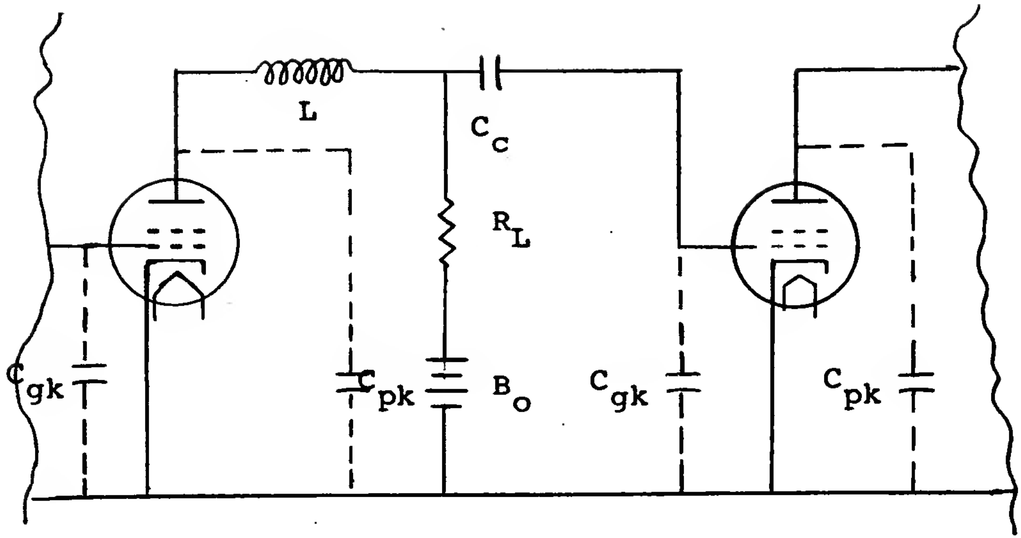
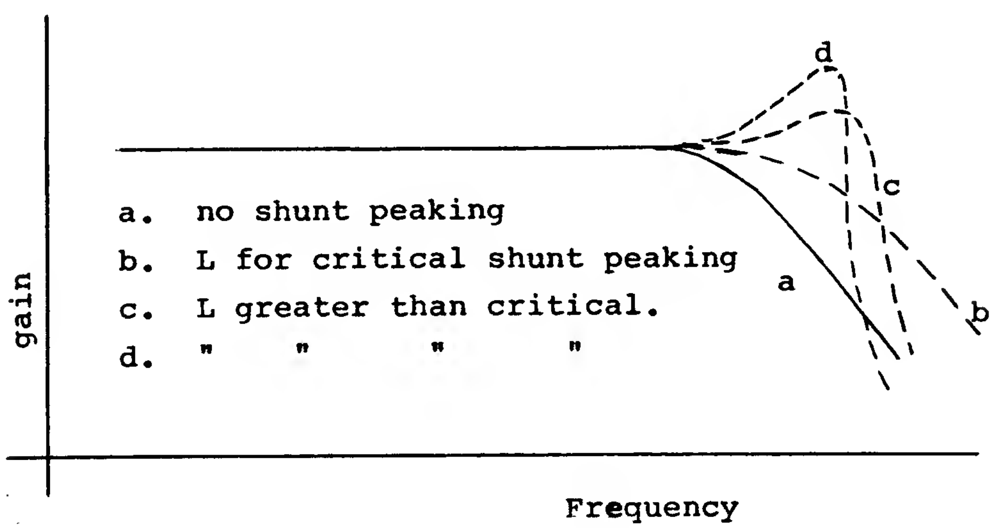


Exhibit A - 2 High Frequency equivalent Circuit

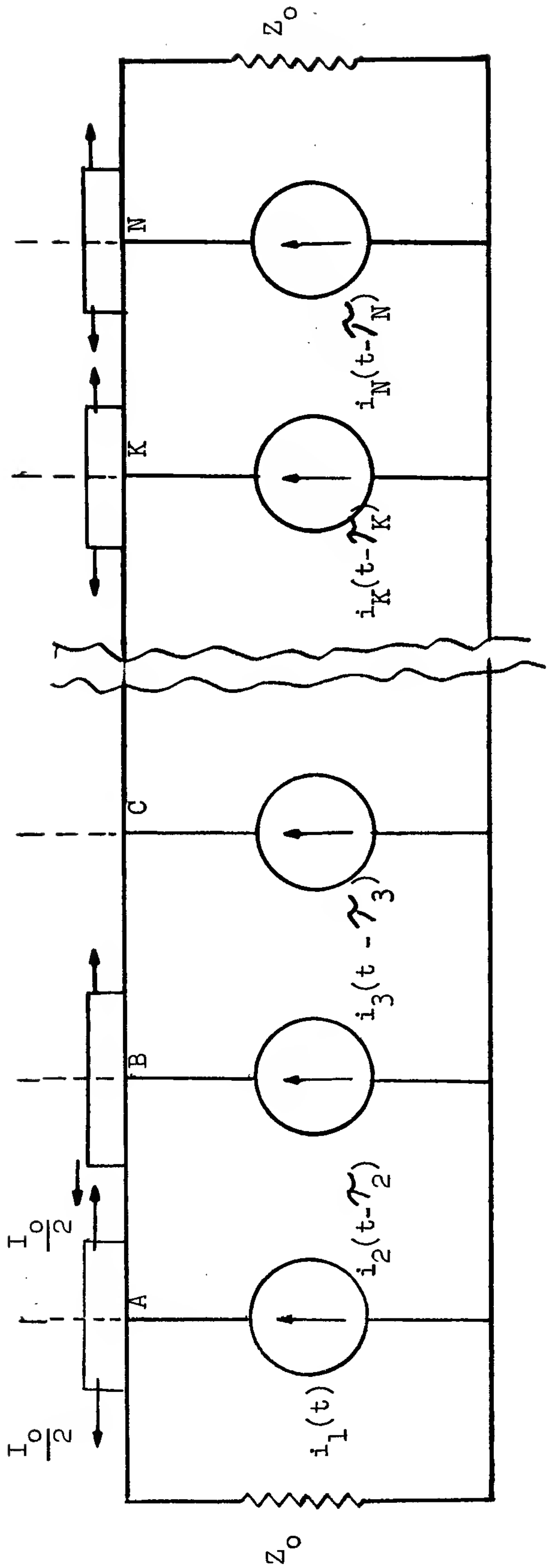


Shunt Peaking Circuit



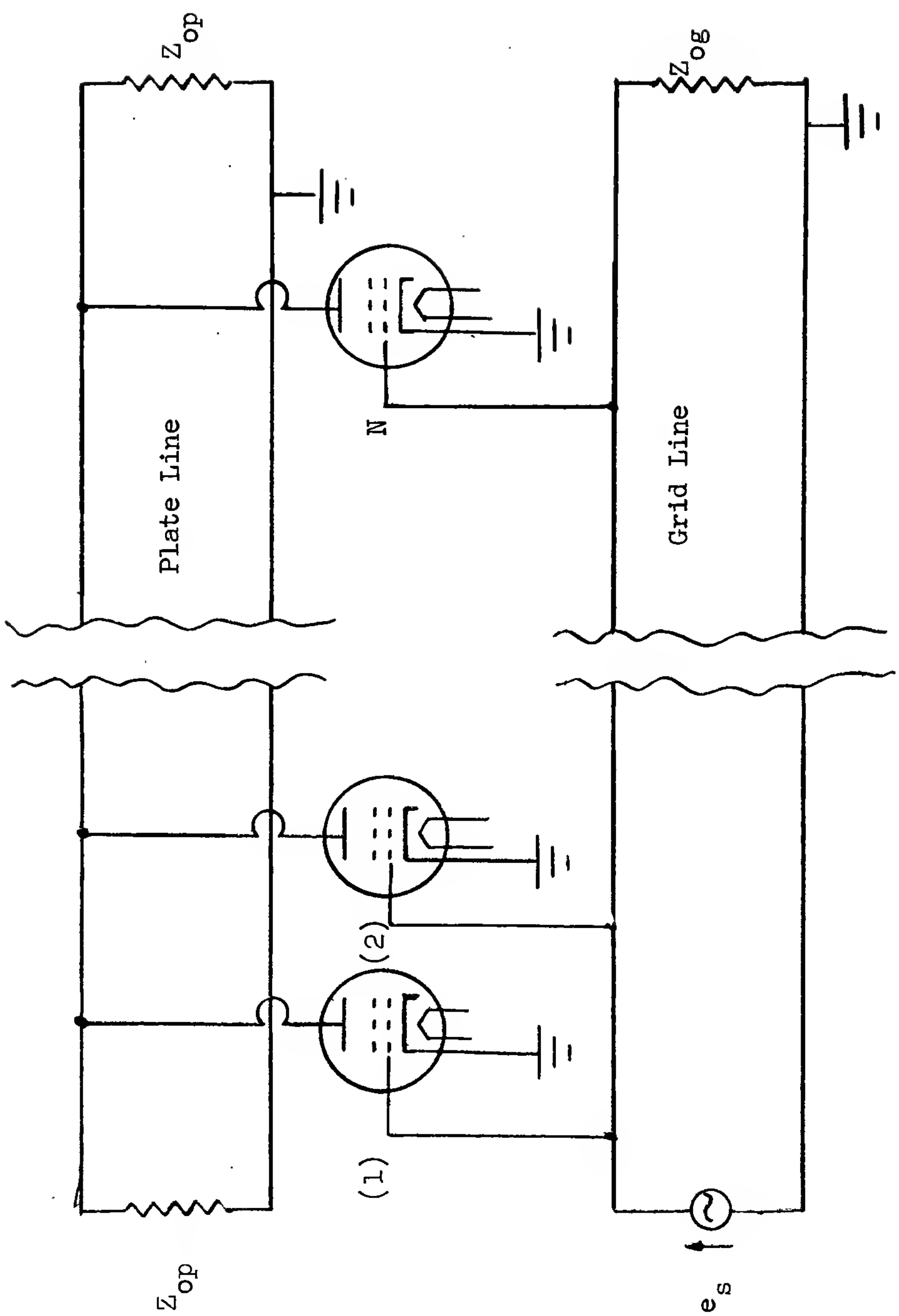
Frequency Response of the Amplifier

Exhibit A - 3



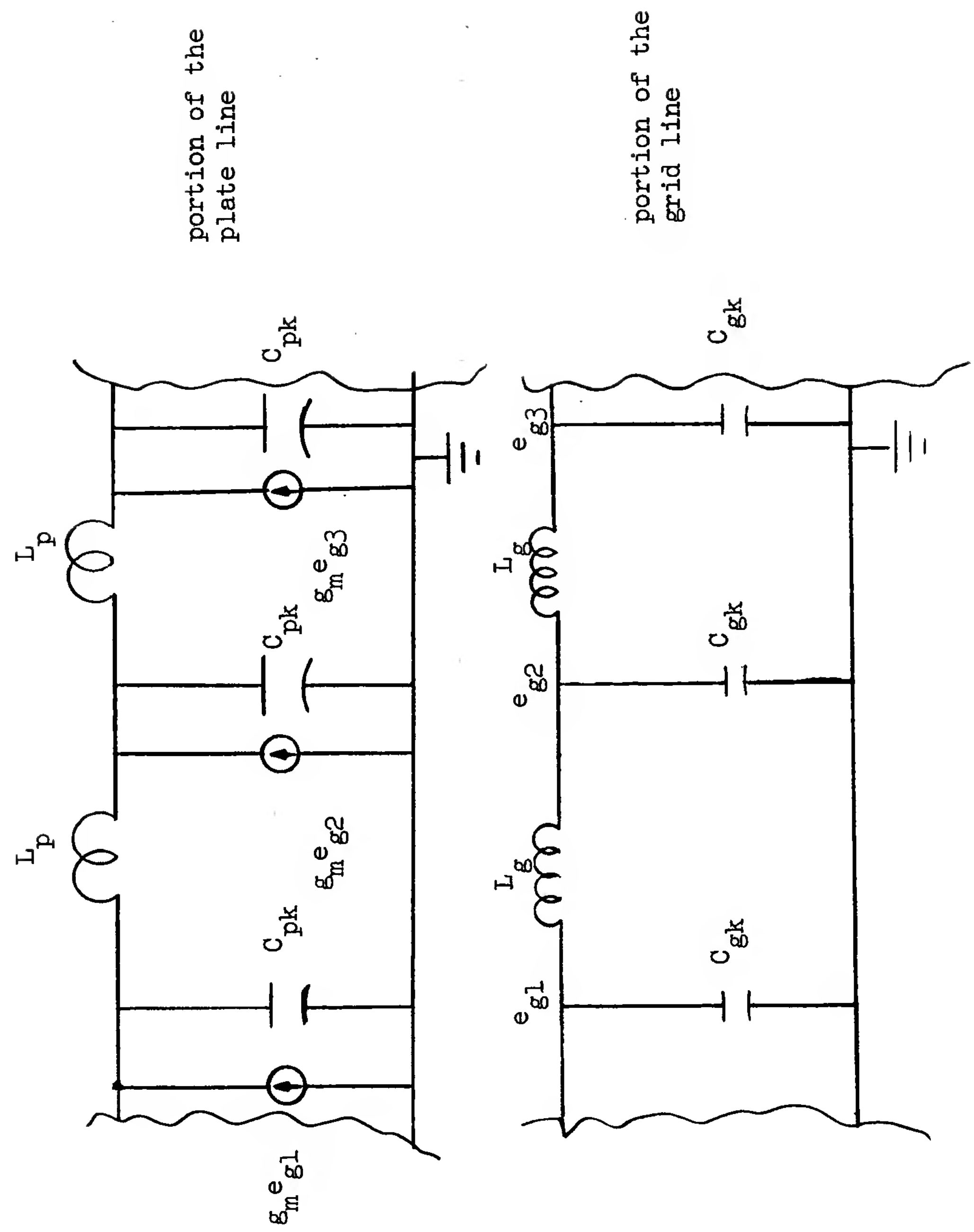
Distributed Amplifier

Exhibit A - 4

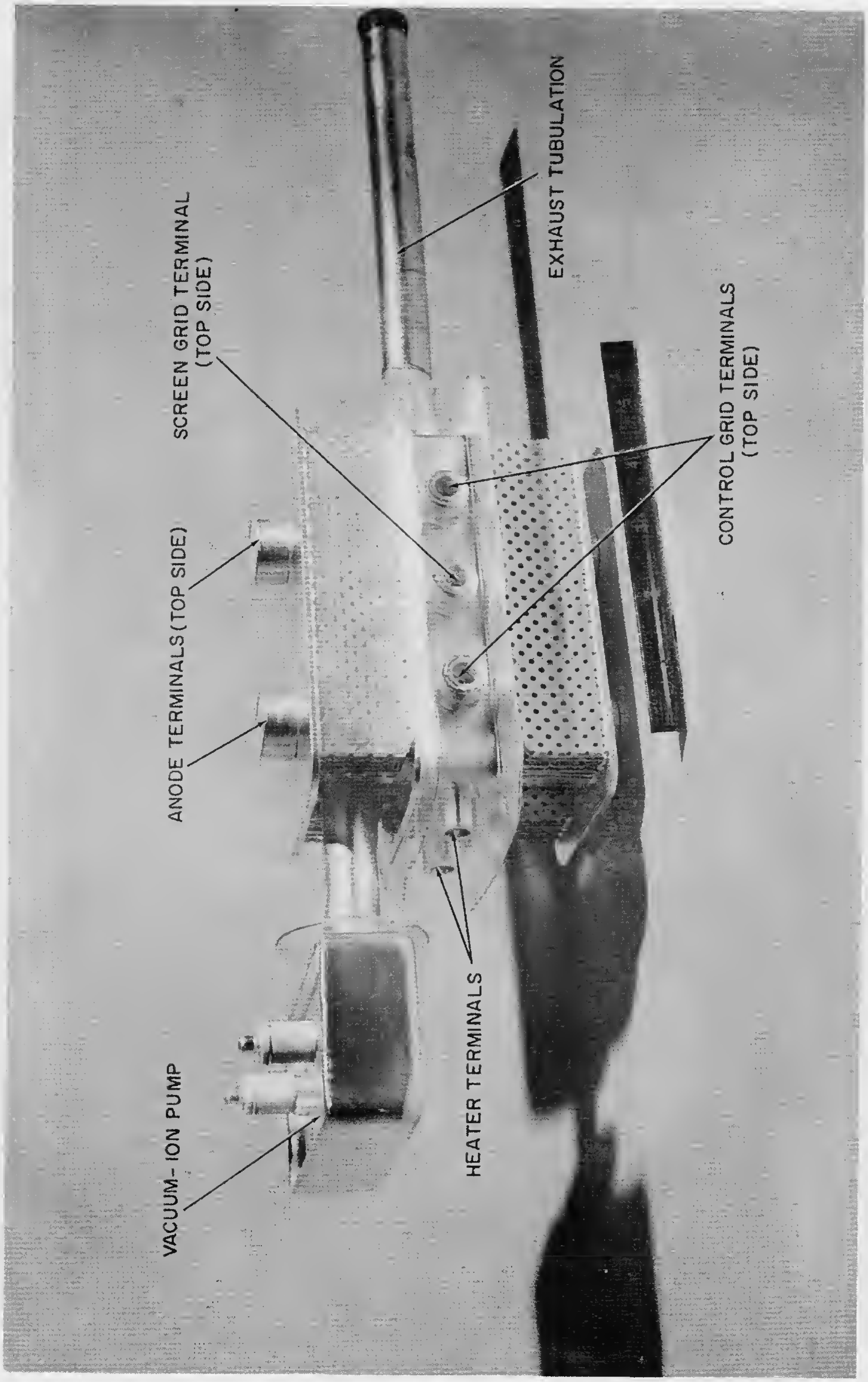


Tubes and grid line to generate the current sources

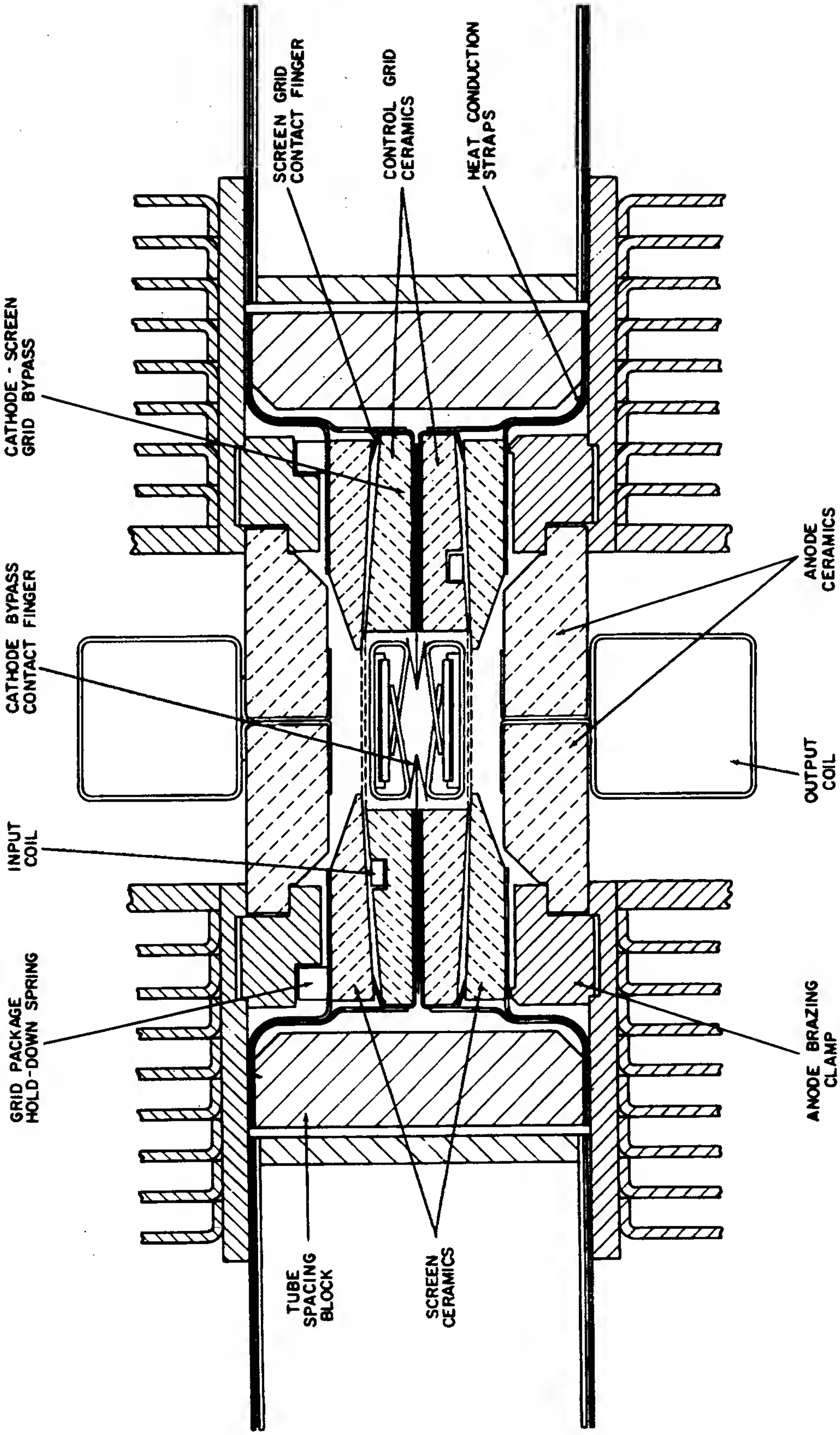
Exhibit A - 5



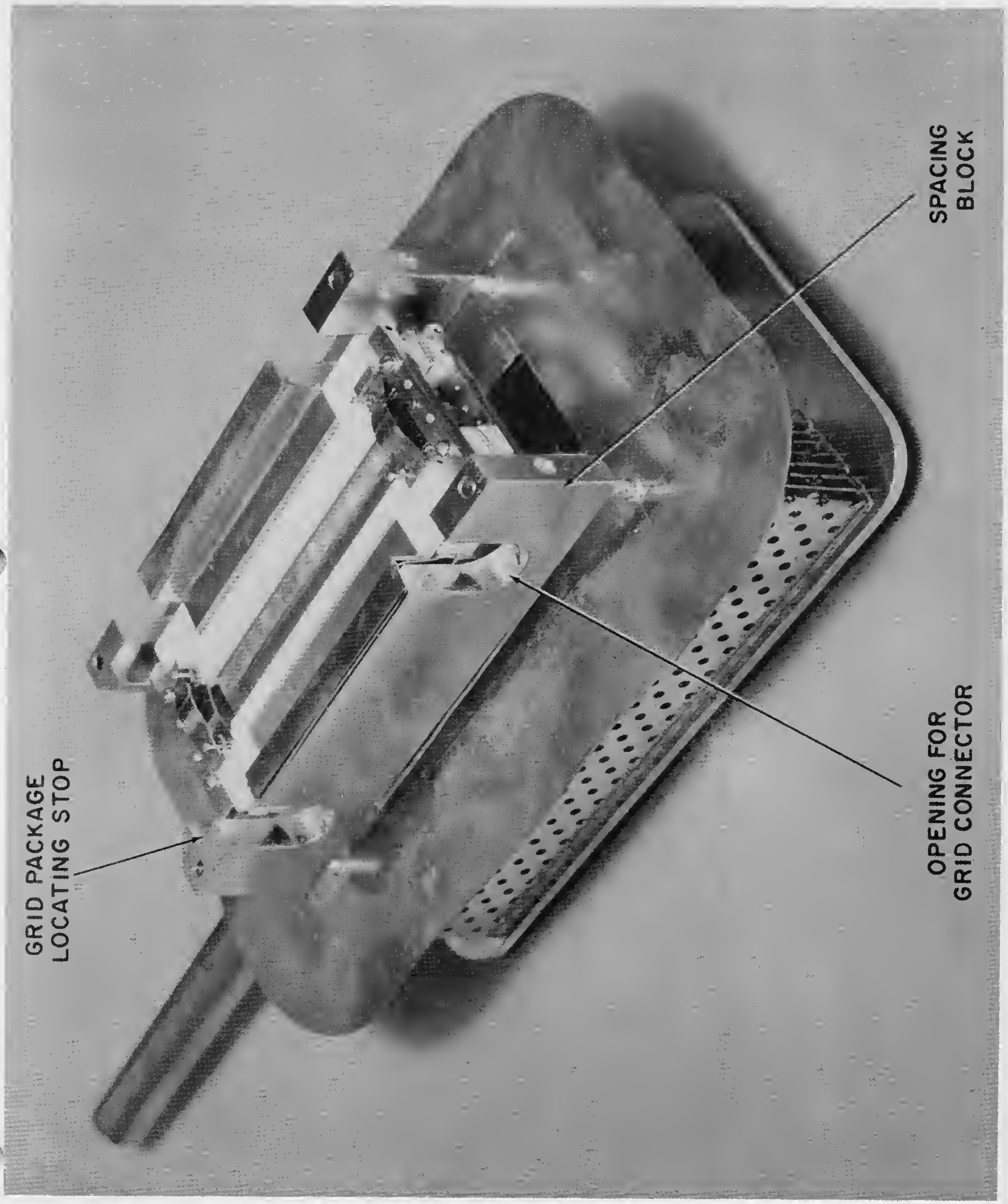
Constant K filter Sections for Plate and Grid Lines



Integrated Distributed Amplifier



Cross-sectional View of the Integrated Distributed Amplifier



Grid Package Assembly

Exhibit A - 9

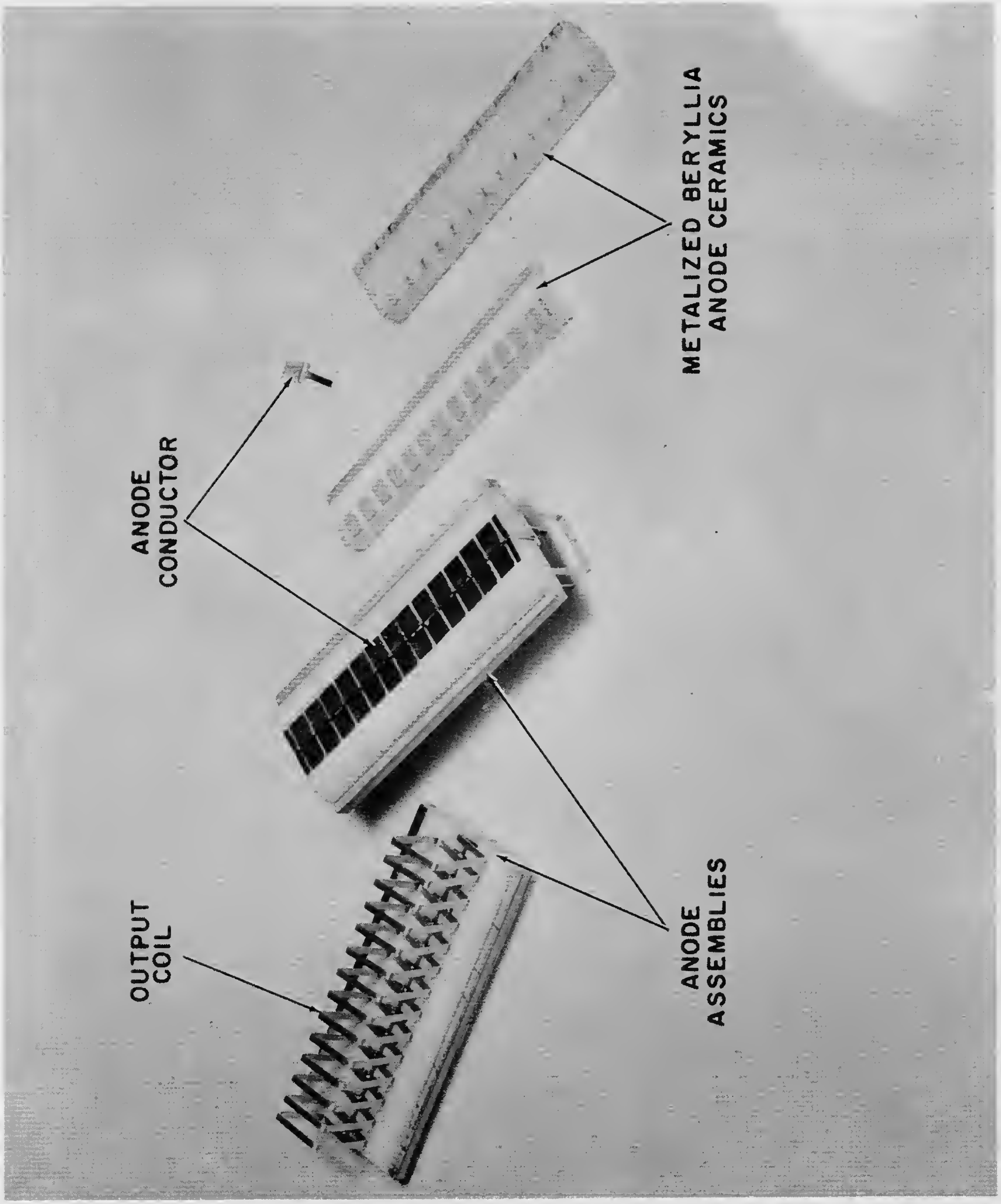
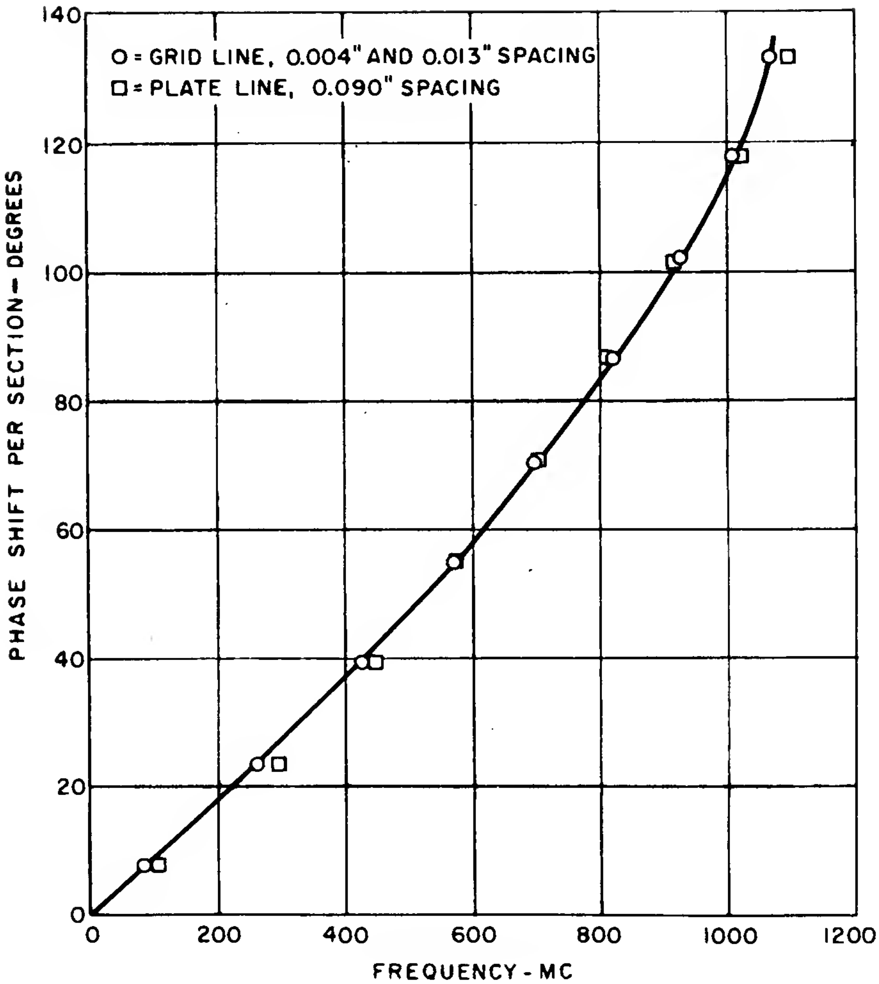


Plate-Line Components



Phase Characteristics of Grid and Plate Lines

Integrated Distributed Amplifier
at
General Electric Company (B)

In the summer of 1960, Ed Craig joined Charles Mayer on the design of the integrated distributed amplifier under contract with the Army Signal Corps. They had agreed that although there were differences in calculated and measured values, using the simplest mathematical model, the tube gave satisfactory performance. They decided to write a computer program to design the integrated distributed amplifier. But to do this they had to know why the calculated Z_{op} and f_{co} were not equal to the measured values. It occurred to them that the mutual inductance from section to section might not be negligible for the plate inductance coil. Looking back on this period, Craig, shaking his head and smiling, said, "We should have been more careful in our assumptions; it now seems impossible that we ignored the mutual inductance effect of the plate line coil. Mayer or myself," Ed continued, "I can't remember who it was now, recognized that the mutual induction effect between neighboring coils might be the factor to which the differences in calculated and measured values may be attributed."

Allowing then for the mutual effect between two successive coils a modified mathematical model was obtained (see Exhibit B-l). Calculations using the geometry of the "plate line" coils showed the mutual inductance (M_p) to be 7.43×10^{-9} henrys which "turned out to be a good portion of the self inductance of the coil itself ($L_p = 27.34 \times 10^{-9}$ henrys)," Craig said. Using these values the characteristic impedance of the plate line and cut off frequency were recalculated.

$$Z_{op} = \sqrt{\frac{L_p + 2M_p}{C_{pk}}} \frac{1}{\sqrt{1 - (\omega/\omega_{co})^2}}$$

$$f_{co} = \frac{(1/\pi)}{\sqrt{L_p C_{pk} \left(1 - \frac{2M_p}{L_p}\right)}} = 2.5 \text{ MHz}$$

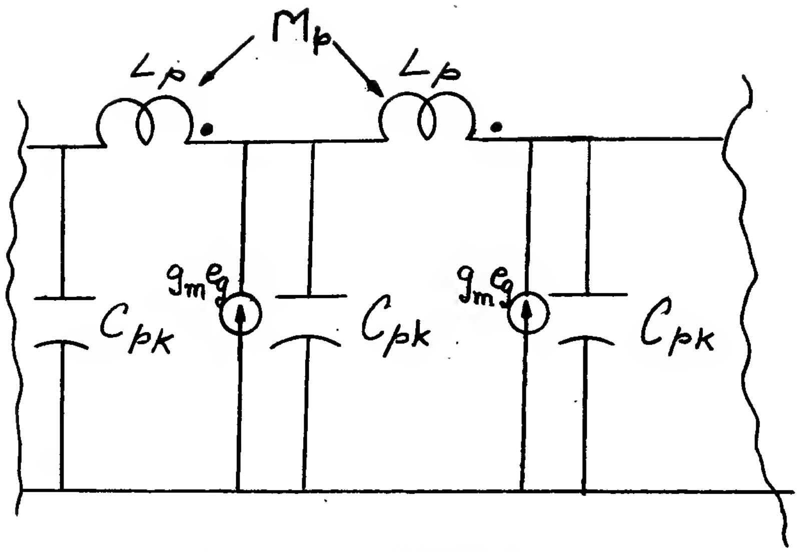
"The mutual inductance actually increased the impedance, you see, to 190 ohms which was the measured value," Ed noted. "However, it turns out that the cut off frequency was now calculated to be in excess of 2.5 MHz."

Perplexed at this outcome they once again reviewed their assumptions: what had they missed this time? How frustrating it is when things don't work out nicely as in textbooks. About this time the project was terminated without the solution to this problem.

After some time the contract was reactivated and in February 1963, Craig and Mayer concluded that there was need for further modification of the circuit assumed. What they assumed to be a purely inductive coil perhaps had significant capacitance between the windings of the plate inductors. Indeed, the inter-winding capacitance (C_L) turned out to be 0.5×10^{-12} farads. Ed wrote the necessary equations for the newly modeled circuit (see Exhibit B-2) and solved for the cut off frequency

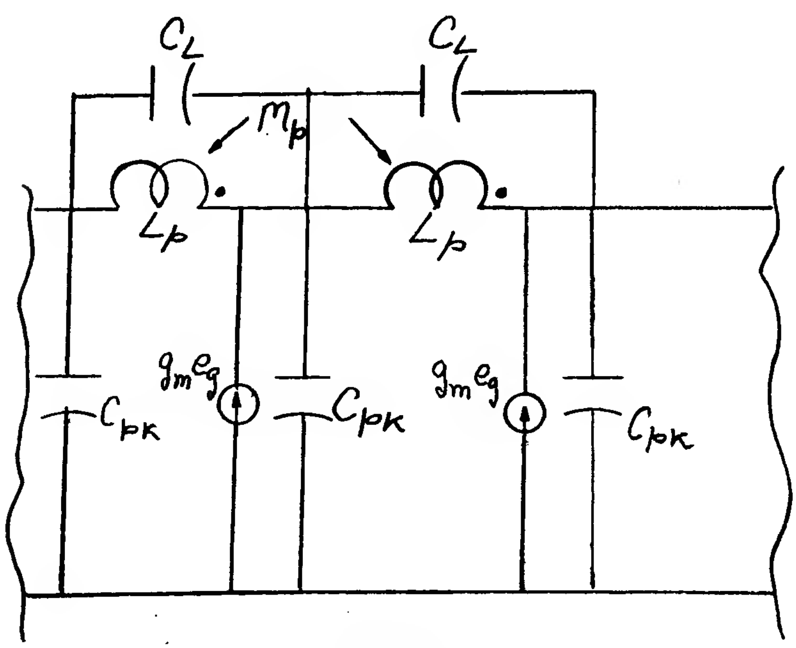
$$f_{co} = \frac{(1/\pi)}{\sqrt{L_p C_{pk}\sqrt{\left(1 - \frac{2M_p}{L_p}\right)\left(1 + \frac{4C_L}{C_{pk}}\right)}}} = 1410 \text{ MHz}.$$

The measured value of the cut off frequency was 1390 MHz; the numbers were now close enough to be explained. A prototype model was completed and tested. The results indicated a power output of 200 watts, a power gain of 13 db, a bandwidth of 600 MHz and a 35% efficiency with class B operation.



$C_{pk} = 1.2 \times 10^{-12}$ fd
$L_p = 27.34 \times 10^{-9}$ h
$M_p = 7.4 \times 10^{-9}$ h

<u>Exhibit B-1.</u> Plate-Line Circuit Modified to Include Mutual Inductance



$C_{pk} = 1.2 \times 10^{-12}$ fd
$L_p = 27.34 \times 10^{-9}$ h
$M_p = 7.4 \times 10^{-9}$ h
$C_L = 0.5 \times 10^{-12}$ fd

<u>Exhibit B-2.</u> Plate-Line Circuit Modified to Include Winding Capacitance

INSTRUCTOR'S NOTE

Teaching Objectives

1. The primary teaching objective of this case is to give a student in electrical engineering a chance to tie in his theoretical knowledge of electronics, electromagnetic field theory, and filter theory.

2. The case provides an opportunity to the student to learn about a device (integrated distributed amplifier) which is not often dealt with in standard textbooks in electronics, electromagnetic fields or filter theory.

3. This case has been successfully used to generate the idea of lumped parameters (constant "k" filter) from distributed parameter circuits (transmission lines).

4. Simple mathematical models assumed by students and engineers alike rarely describe a physical device accurately. In this case the idea of the mutual inductance and the stray capacitance of the plate line inductive coil is an example that could drive home this point to the students.

5. The instructor could ask the students what their position on R & D research would be if they were in Bill Teare's place.

References:

Much of the treatment given in this case is abundantly available in basic textbooks on electronics, applied electromagnetic field theory (transmission lines) and basic circuit theory. There are two books with some reference to the integrated distributed amplifier as a device:

1. Pulse, Digital, and Switching Waveforms, by Millman and Taub (McGraw Hill, 1965) pp. 171-177, (see also Appendix C).

2. Electronic and Radio Engineering, by Frederick E. Terman (McGraw-Hill, 1955) pp. 313-315, (see also Chapter 9).

Electromagnetic transmission line equations are documented in textbooks such as

1. Circuit Analysis of Transmission Lines, by John L. Stewart (John Wiley & Sons, 1958).
2. Engineering Electromagnetics, by W. H. Hayt (McGraw-Hill, second edition, 1967).

The characteristics of constant "k" filter sections are well documented in standard network analysis textbooks. For example

1. Network Analysis, by Van Valkenberg (Prentice Hall, 1955) Chapter 13, in particular section 13-6.
2. Transmission Lines and Networks, by Walter C. Johnson (McGraw-Hill, 1950) Chapter 15, in particular section 15-2.

Summary of Theory:

(i) Transmission Line Characteristics:

For a "loss-less" transmission line, Telegraphers Equations are

$$\frac{d^2E}{dx^2} = -\omega^2 LC\,E$$

$$\frac{d^2I}{dx^2} = -\omega^2 LC\,I \qquad (1\text{-}1)$$

where:

E & I, are voltages and currents on the line at a distance x measured from the load.

ω, is the operating frequency in radians/sec.

L, is the inductance per unit length in henrys/unit length.

C, is the capacitance per unit length of the line in farads/unit length. Solution of these equations are of the form

$$E = E_1 e^{j\beta x} + E_2 e^{-j\beta x}$$

$$I = \frac{E_1}{Z_o} e^{j\beta x} - \frac{E_2}{Z_o} e^{-j\beta x} \qquad (1\text{-}2)$$

Wave traveling from the source to the load (incident)	Wave traveling from the load to the source (reflected)

Everywhere on the line the ratio of the voltage to the current in each individual traveling wave is defined as the characteristic impedance Z_o

where $$Z_o = \sqrt{\frac{j\omega L}{j\omega C}} = \sqrt{\frac{L}{C}} \text{ ohms} \qquad (1\text{-}3)$$

and the phase of each traveling wave advances (for incident wave) or retards (for reflected wave) an amount β radians per unit distance.

where $$\beta = \omega\sqrt{LC} \qquad (1\text{-}4)$$

If a wave, say the incident, travels a length of a loss-less transmission line d meters from a reference point the phase of this wave advances βd radians with respect to the reference. Since the wave velocity v_p meters/sec is dependent on the parameters of the line

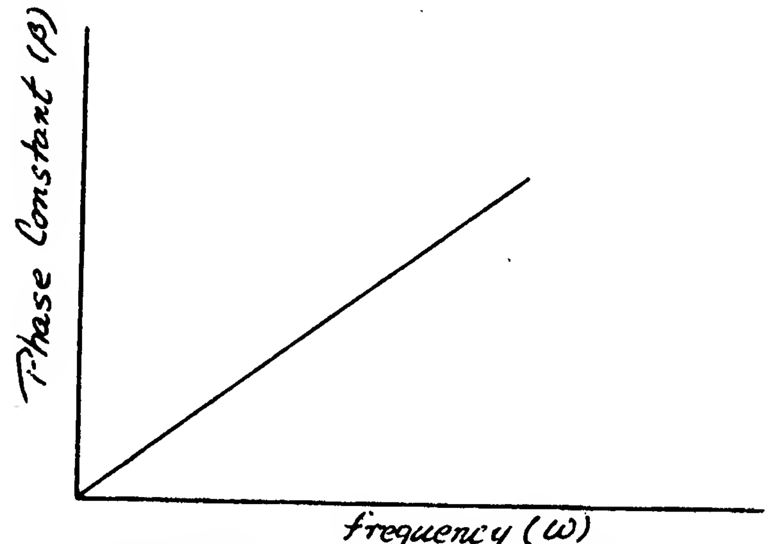
$$v_p = \frac{1}{\sqrt{LC}} \text{ meters/sec} \qquad (1\text{-}5)$$

the delay in time T_d sec before the wave reaches a distance d meters from the reference point, where $T_d = 0$ (say), is

$$T_d = \frac{d}{v_p} = \frac{d}{\frac{1}{\sqrt{LC}}} = \frac{d}{(\omega/\beta)} = \frac{\beta d}{\omega} \text{ seconds} \tag{1-6}$$

or, $T_d = \dfrac{\text{phase advance of the wave in radians}}{\text{frequency in radians/sec.}}$

The $(\omega - \beta)$ diagram for a "lossless" line is shown below can be seen here that the (distributed parameter) transmission line is bandwidth unlimited.

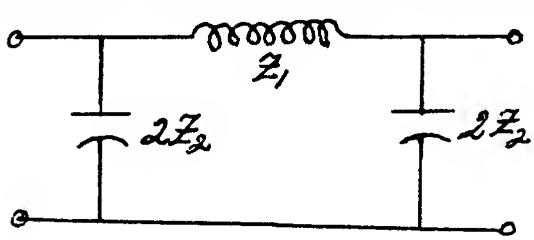


$(\omega - \beta)$ diagram for a lossless transmission line

(ii) Constant "k" filter characteristics:

A π section prototype filter of L & C elements connected in a ladder network yields similar characteristics as discussed in part (i) but for the disadvantage of bandwidth limited operation. However the saving in physical space and volume still justified its use in place of the distributed parameter transmission line.

Low Pass π Section Constant "k" prototype filter:

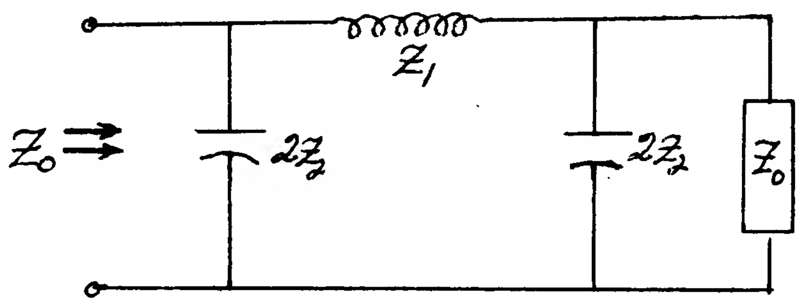


$Z_1 = j\omega L$

$Z_2 = \dfrac{1}{j\omega C}$

If $Z_1 Z_2 = \frac{L}{C}$ = "k", a constant, the filter section is called a constant "k" prototype.

The image or the characteristic impedance (Z_o) of such a filter section is defined as the input impedance of the section when the section is terminated in its characteristic impedance also



by simple circuit theory manipulations

$$Z_o = \sqrt{\frac{Z_1 Z_2}{(1 + \frac{Z_1}{4Z_2})}} \tag{2-1}$$

or,

$$Z_o = \sqrt{\frac{L}{C}} \frac{1}{\sqrt{(1 - \frac{\omega^2 LC}{4})}} \tag{2-2}$$

A pass band is obtained when the quantity $(Z_1/4Z_2)$ in equation is such that

$$- 1 < \frac{Z_1}{4Z_2} < 0 \tag{2-3}$$

In the pass band, if the propagation constant is $\gamma = \alpha + j\beta$ where α is the attenuation constant in nepers per section and β is the phase constant in radians per section;

$$\left.\begin{aligned} &\alpha = 0 \\ &\cos\beta = 1 + \frac{Z_1}{2Z_2} = \left(1 - \frac{\omega^2 LC}{2}\right) \end{aligned}\right\} \tag{2-4}$$

In the "attenuation band"

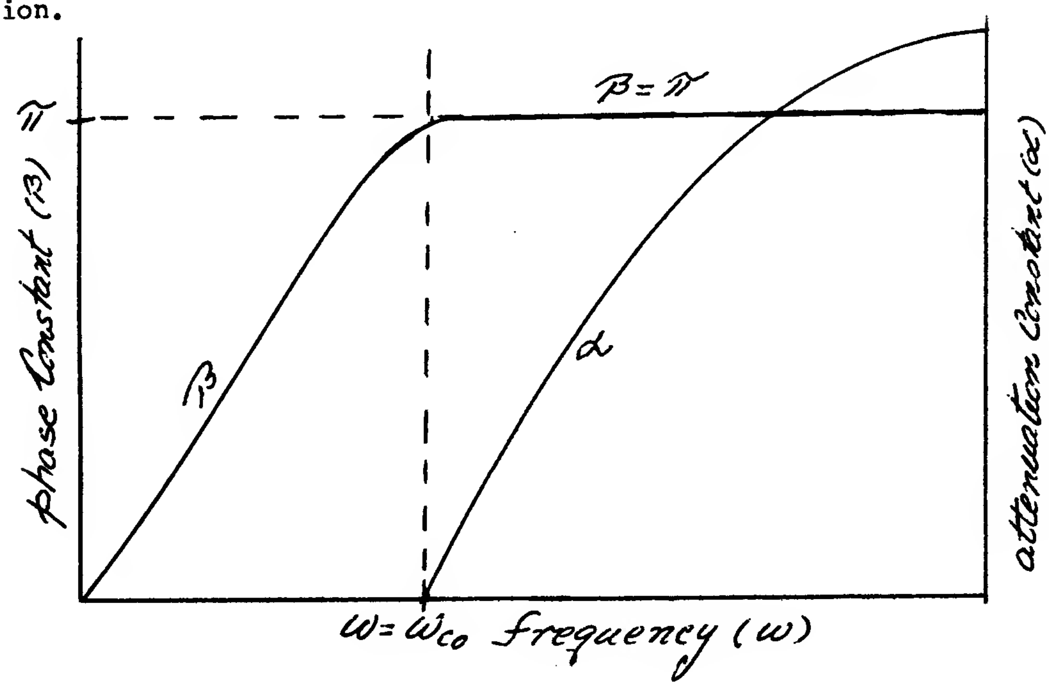
a. when $\frac{Z_1}{4Z_2} > 0$, then

$$\left.\begin{aligned} &\cosh\alpha = 1 + \frac{Z_1}{2Z_2} = \left(1 - \frac{\omega^2 LC}{2}\right) \\ &\beta = 0 \end{aligned}\right\} \tag{2-5}$$

b. when $\frac{Z_1}{4Z_2} < -1$, then

$$\left.\begin{aligned} &\cosh\alpha = -1 - \frac{Z_1}{2Z_2} = \left(\frac{\omega^2 LC}{2} - 1\right) \\ &\beta = \pm\pi \end{aligned}\right\} \tag{2-6}$$

A plot of the phase and attenuation with respect to frequency as shown below indicates that the constant "k" filter will have a bandwidth limited operation.



as indicated on the plot there exists a frequency called a nominal cut off frequency (f_{co}) given by

$$\left.\frac{Z_1}{4Z_2}\right|_{@ f = f_{co}} = -1 \tag{2-7}$$

$$\therefore \quad f_{co} = \frac{1}{\pi\sqrt{LC}} \tag{2-8}$$

or

$$\omega_{co} = \frac{2}{\sqrt{LC}}$$

Substituting this in equation (2-2)

$$Z_o = \sqrt{\frac{L}{C}} \cdot \frac{1}{\sqrt{1 - (\frac{\omega}{\omega_{co}})^2}} \tag{2-9}$$

A useful parameter in the case is the time delay per section

$$T_d = \frac{1}{\pi f_{co}} = \frac{1}{\sqrt{LC}} \text{ seconds.} \tag{2-10}$$

Some questions the instructor could ask the students:

1. Derive the voltage gain bandwidth product relation for a tetrode amplifier.
2. Show that for a 6AK5 tube whose parameters are:

   $g_m = 5{,}100 \times 10^{-6}$ mhos

   $C_{pk} = 2.8$ μμ fd.

   $C_{gk} = 4.0$ μμ fd.

   the voltage gain bandwidth product does limit the use of such tubes for wideband, high gain amplifiers.
3. Show that for n identical amplifier stages, with voltage gain A and cut off frequency f_{co}, if cascaded, would produce a higher gain but that the overall bandwidth would be lower than that due to each stage.
4. Describe the integrated distributed amplifier action and principle.
5. Trace the path of equal time delay in this amplifier.
6. Find the voltage gain of this amplifier in terms of the transconductance of the tube (g_m).
7. Show that the characteristic impedance of a constant "k" low pass filter section is

$$Z_o = \sqrt{\frac{L}{C}} \cdot \frac{1}{\sqrt{1 - (\omega/\omega_{co})^2}}$$

8. Could this amplifier be used up to the cut off frequency f_{co}?
9. Mayer's initial calculation yielded $Z_{op} = 151\Omega$, at what frequency was it calculated?
10. Ed said, "In order to have a distributed amplifier action it is very important that the phase characteristics of plate and grid lines be linear and identical." Why?

11. Did Mayer and Ed do what a typical engineer would do under the circumstances of having encountered obvious difference between calculated and experimental values?

12. Would you--if you were an engineer--say, "we were pragmatic" and overlook this obvious difference or would you pursue the analytic approach further?

13. If you were to continue the analytic approach further what would you do?